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Electrochemical drilling using alternating current *

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The attraction of using a.c. compared with d.c. is the opportunity it offers to simply transform normal workshop power supply down to a sensible potential value for electrochemical machining without having to incorporate rectifying equipment. Its success will normally depend on the ability to find tool materials which are not affected by electrolytic action while at positive potential and on the normal 50/60 Hz mains frequency being satisfactory. However, the possible use of higher frequencies should not be ruled out for small area work where total current can be in 10 s rather than 100 or 1000 s of amps; a high frequency oscillator could then be a sensible source of power. This paper is based on experimental work carried out using easily obtained tool electrode materials and illustrates the practical feasibility of a.c. for industrial use.

Nomenclature

E = sum of electrode potentials
E_w = electrochemical equivalent of workpiece material
f = feed rate
h = gap
h_m = mean gap
H_z = frequency
k = conductivity
t = time
V_{max} = maximum applied voltage
V_{mean} = mean useful voltage
θ = angle = ωt
η_a = anode overpotential
η_c = cathode overpotential
ρ = density
ω = angular frequency = 2πHz.

1. Introduction

The application of a.c. for E.C.M. was suggested as far back as 1962 in a British Patent [1], but serious work was not carried out until Johnson and Brown [2] carried out a feasibility study in 1970 for the British Ministry of Technology. One of their tool materials was graphite which, although electrically conductive, is electrolytically inert so that during the anodic-tool half-cycle only gassing of the electrolyte solution takes place. However, because current will be utilized to produce this gas, low machining efficiency is likely. Mechanical wear due to the rapidly flowing electrolyte solution was lowered to an insignificant level by the use of high density graphite treated with oil.

Johnson and Brown also showed that with certain materials such as titanium diboride and tantalum, a layer of oxide forms on the tools and that this layer rectifies the current flowing across the cell in somewhat similar fashion to that by metal rectifiers. However, with potentials above 20 V r.m.s. they obtained incomplete rectification and consequently observed machining of the tool. While the workpiece is anodic such rectifying tool materials must operate fundamentally as with d.c. and, therefore, in accordance with Faraday's Laws. While the workpiece is cathodic, a layer must exist on the tool surface, or at its junction with the electrolyte solution, in which infinite resistance occurs to prevent current flow so that neither machining nor gassing takes place. In the practical

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* The contents of this paper were reported by C. F. Noble at the First International Conference on E. C. M., Leicester University, March, 1973.

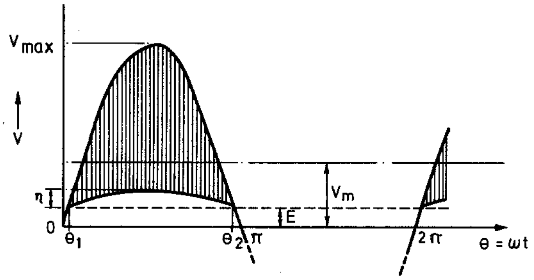
work described herein, commercially pure titanium and aluminium were found to operate successfully as drilling tool electrodes when machining Nimonic 100 workpieces and using a 10% aq. electrolyte solution of sodium nitrite. However, feed rate to date has been less than 2 mm min.$^{-1}$ compared with more than 6 mm min.$^{-1}$ during d.c. drilling [3].

2. Theory

Mean useful voltage

$$V_m = \frac{1}{2\pi}\int_{\theta_1}^{\theta_2}[V_{\max}\sin\theta - E - (\eta_a + \eta_c)\sin\theta]\,d\theta, \tag{1}$$

where $\theta_1 = \sin^{-1} E/V_{\max}$ and $\theta_2 = (\pi - \theta_1)$. Overpotential is assumed to vary sinusoidally.



Assuming $\theta_1 \to 0$, $\theta_2 \to \pi$, then

$$V_m \simeq \frac{1}{2\pi}\int_0^{\pi}\{V_{\max}\sin\theta - (\eta_a + \eta_c)\sin\theta - E\}\,d\theta. \tag{2}$$

Experimentally, it was found that the minimum r.m.s. potential to avoid short circuiting was approximately 5 V, e.g. see extrapolated value in Fig. 3, so that Equation 2 reads:

$$V_m \simeq \frac{V_{\max}}{\pi} - 2 = \frac{\sqrt{2}(V_{\mathrm{rms}})}{\pi} - 2 \simeq 0{\cdot}45\,V_{\mathrm{rms}} - 2. \tag{3}$$

This corresponds to $\eta_a = \eta_c = 1\,\mathrm{V}$, $E = 2{\cdot}7\,\mathrm{V}$ which appears reasonable.

It can be shown that under equilibrium conditions the mean gap

$$h_m \simeq \frac{kE_w V_m}{\rho f},$$

now

$$h_{\min}^{\max} \simeq h_m \pm \left(\frac{f}{2\,\mathrm{Hz}}\right). \tag{4}$$

Thus, the limiting condition (short circuit) is given when $h_{\min} = 0$,

$$\therefore \quad \frac{f}{2\,\mathrm{H_z}\,h_m} < 1. \tag{5}$$

Inserting Equations 4 into 5 reveals:

$$\frac{\rho f^2}{2\,\mathrm{H_z}\,kEV_m} < 1. \tag{6}$$

There would not appear to be any gap variation problem when using normal frequency levels. At 50 Hz and a feed rate as high as 25 mm min.$^{-1}$, the gap variation will only be ± 4 μm so that at the normally much slower feed rates, when the interelectrode gap will be larger, any changes in gap size will be infinitesimal. However, the voltage gradient will increase substantially during the cycle. Useful maximum voltage $V_{\max} \simeq \pi V_{\mathrm{mean}}$. Thus, with conditions set to give the same mean gap and feed rate as in d.c. operations the voltage gradient will be approximately 200% greater. This is serious from an electrical sparking point of view and may be the main cause of any feed rate restrictions observed.

3. Results – Nimonic 100 workpiece, 10% aq. electrolyte solution of $NaNO_2$

3.1. *Titanium drill*

(*O*/*D* – 1·35 mm, *I*/*D* – 1·00 mm). Length/diameter ratio < 50 to avoid undue vibration. Insulated with Terebec CH33 resin, 75 μm thick).

Machining of the workpiece occurs during the negative half-cycles shown in Fig. 1a–d. The apparent change in trace size with frequency is not significant – it is due to a change in magnification. Rectification is observed to be gradually lost over the range but with frequency ⩽ 50/60 Hz it is virtually complete.

The effect is further exemplified in Fig. 2 where the time to rectify is shown to be a small portion of the half cycle time at low frequencies but approaching a non-rectified condition above 1 kHz. ($\mathrm{Log_{10}H_z} > 3$).

It appears that the higher the rate of change of voltage ($\alpha\,\mathrm{H_z}$) the lower will be the time to rectify. Thus, the quality of the rectifying layer is not determined by a constant time interval, but

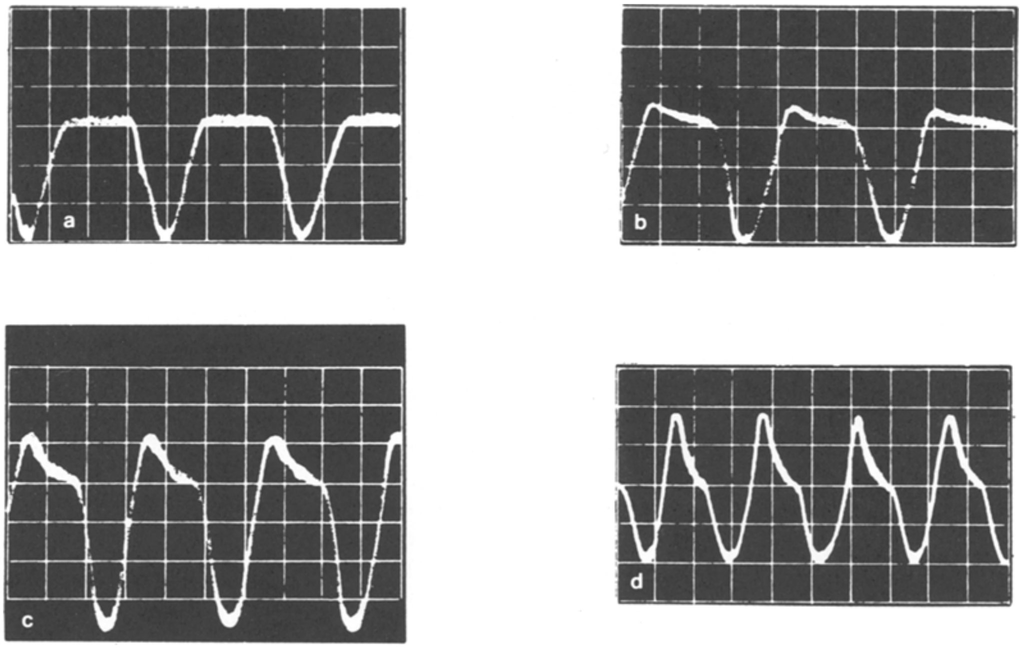


Fig. 1. Current wave-form versus frequency for titanium drill at 15 V r.m.s., 0·25 mm min^{-1} feed rate. Current density: workpiece $\simeq$ 15 A cm^{-2}; drill $\simeq$ 56 A cm^{-2}. (a) 5 Hz; (b) 50 Hz; (c) 300 Hz; (d) 2000 Hz.

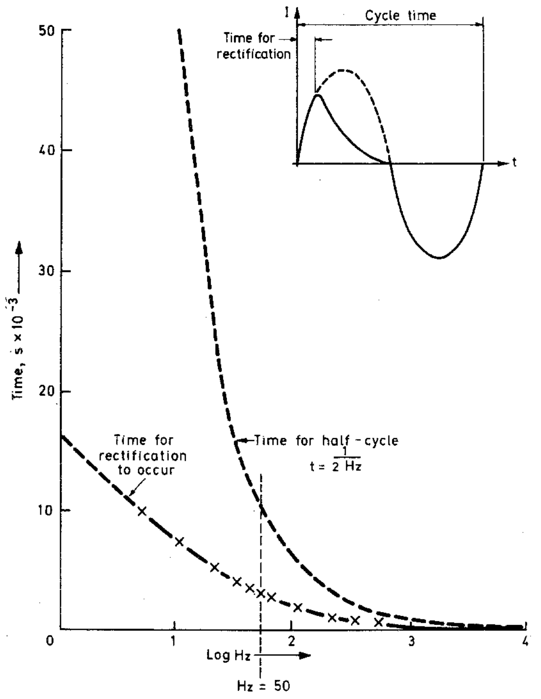


Fig. 2. Time for rectification versus frequency for titanium drill.

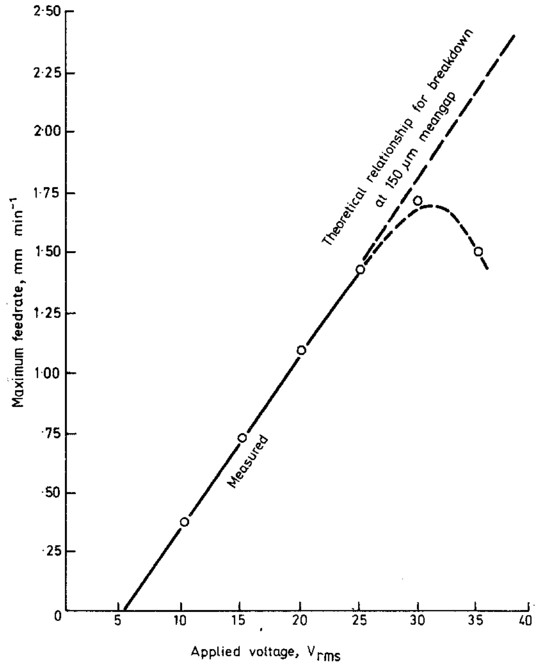


Fig. 3. Maximum feed rate versus applied voltage for titanium drill at 50 Hz.

probably rather by the energy required for its formation. It will be observed that although time reduces, voltage at breakdown increases (Fig. 1).

Fig. 3 illustrates the feed rate $\sim V_{\mathrm{r.m.s.}}$ relationship at limiting conditions (sparking) with a 50 Hz

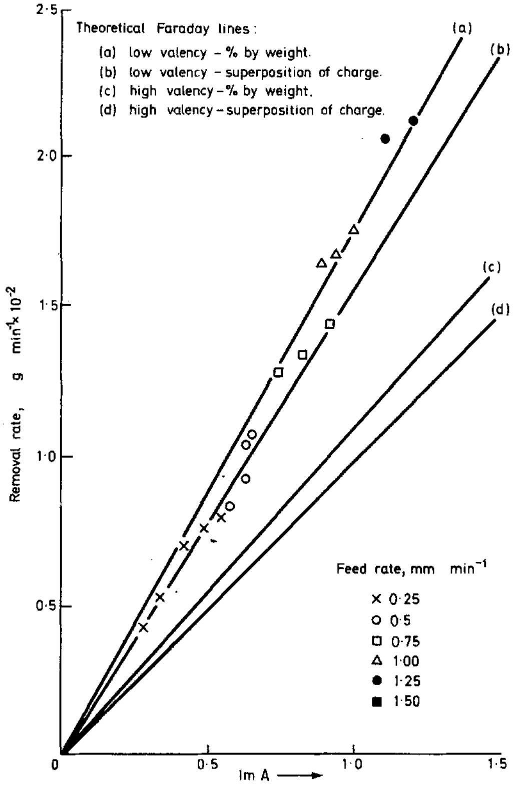


Fig. 4. Removal rate from workpiece versus mean current for titanium drill 50 Hz, 10–30 V r.m.s., 180 cm^3 min^{-1} solution flow rate.

supply. The results are seen to be very close to a theoretical relationship based on low valency superposition of charge for breakdown at a mean gap of 150 μm. At voltages higher than 35 V r.m.s. rectification disappeared and some wear of the drill was observed. This value is of interest because with the difficulty of machining titanium under normal d.c. conditions 40 V d.c. may be necessary with standard E.C.M. electrolyte solutions (e.g. reference [4]) (and especially with sodium nitrite solutions) in order to be sure of breaking down the highly passive layer. However, we see that when the frequency is high, rectification disappears at lower voltages (e.g. 15 V r.m.s. in Figs. 1 and 2).

Fig. 4 illustrates removal rate ~ mean current at 50 Hz. The proximity of the results to the 100% efficiency Faraday lines based on low valency reactions is very marked, especially in view of the variation of voltage and feed rate included in the results. However, other results have shown that when electrolyte solution flow rate is increased above 200 cm^3 min^{-1} there is a tendency for reduced efficiency but it is never less than that predicted by high valency calculation. Whether or not the results favour the super-position of charge or the wt% methods for calculating theoretical relationships is for the reader to decide but other considerations may be important, e.g. Nimonic 100 includes 4/6% Al and 1/2% Ti which form intermetallic compounds with Ni. These compounds are likely to passivate and thus become isolated islands as surrounding elements are

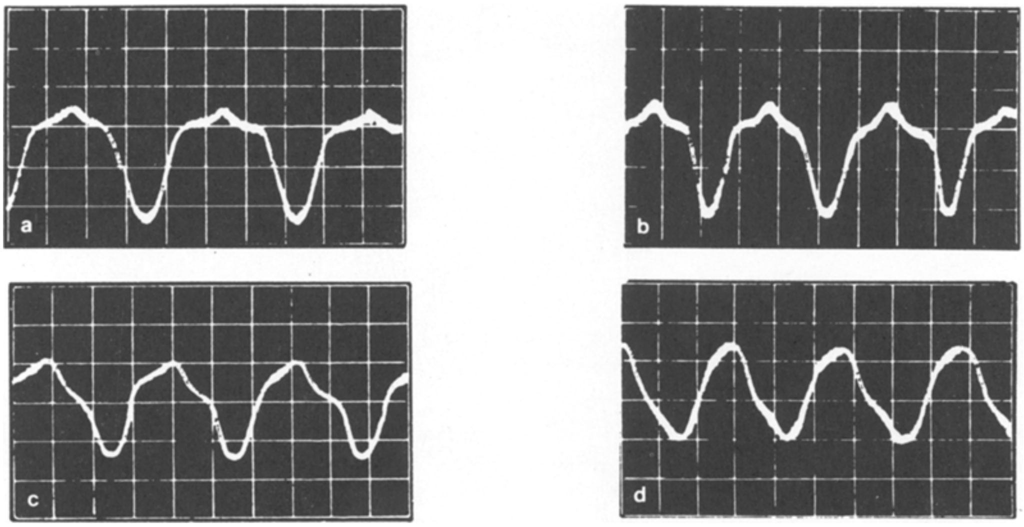


Fig. 5. Current wave-form versus frequency for aluminium drill at 15 V r.m.s., 0·25 mm min^{-1} feed rate. Current density: workpiece ≃ 15 A cm^{-2}, drill ≃ 36 A cm^{-2}. (a) 50 Hz; (b) 600 Hz; (c) 3000 Hz; (d) 8000 Hz.

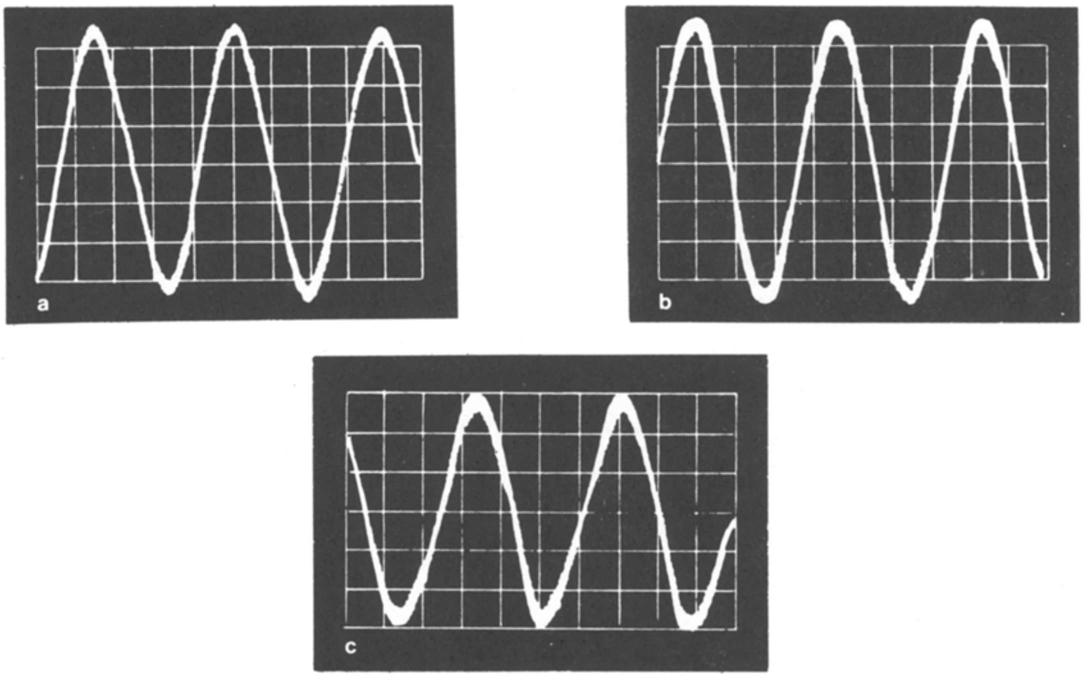


Fig. 6. Current wave-form versus frequency for graphite drill at 15 V r.m.s., 0·25 mm min^{-1} feed rate. Current density: workpiece ≃ 15 A cm^{-2}, drill ≃ 19 A cm^{-2}. (a) 50 Hz; (b) 500 Hz; (c) 5000 Hz.

machined away; they are then simply washed away with the flowing electrolyte solution. This form of Al, Ti and Ni loss gives a false impression of electrolytic removal [5].

Figs. depicting overcut characteristics have not been included but it will be of interest to the reader to observe that its value was approximately $\frac{1}{2}$ × leading gap. Reference [6] gives a value of 1·3 × leading gap under d.c. conditions. This sizeable difference is surprising and until further work is carried out an explanation cannot be offered. However, it may well be a very useful characteristic of a.c. operation when accurate work is desirable.

3.2. *Aluminium drill*

(*O*/*D* – 3·95 mm, *I*/*D* – 3·05 mm, insulated with 150 μm tape). Machining of the workpiece occurs during the negative half-cycles shown in Figs. 5a–d. The apparent change in trace size with frequency is not significant. As with the titanium drill, rectification gradually disappears with frequency increase, but the mode of rectification has an additional characteristic. A small current reversal is observed at mid-half cycle. Since this persists throughout the frequency range it cannot be a function of rate of change of potential. Rather it indicates that conduction is re-established when the voltage rises above a certain critical value. Further experiments are necessary to establish whether or not it would be more correct to refer to a critical voltage gradient. As with the titanium drill, rectification broke down at 50 Hz with 35/40 V r.m.s. Mean current was then almost zero and of a very unstable nature.

3.3. *Graphite drill*

(Manufactured from arc lamp electrodes – *O*/*D* – 6·75 mm, *I*/*D* – 3·05 mm insulated with Terebec CH33 resin, 75 μm thick). Machining of the workpiece occurs during the negative half-cycle shown in Figs. 6a–c which illustrate the current characteristics during operation of the graphite drill at 50, 500 and 5 kHz. As expected, no rectification occurs but neither was there any substantial loss of graphite. What little occurred was probably due to abrasion arising from the flow of contaminated electrolyte solution.

It is important to realize that, since current flows during the reversal portion of the cycle, utilization cannot be greater than 50% efficient. This could be a serious factor in selecting graphite tooling for industrial use unless there is some other over-riding advantage, e.g. tool manufacturing costs, accuracy in performance. For drilling small diameter holes, graphite does not appear to be satisfactory if large length/diameter ratios are involved – it is far too brittle. However, it was possible to operate the drill at 1·25 mm/min feed rate.

4. General conclusions

Titanium, aluminium and graphite are attractive, readily available, tool materials for E.C. machining with alternating current. At normal mains frequency of 50 Hz, both titanium and aluminium rectify readily. Titanium offers Faraday efficiencies of the order of 100% and there is no reason to doubt a similar performance from aluminium, although the associated voltage level and tool wear may prove more important in this respect. Whilst a totally different behaviour occurs with graphite and efficiency of current utilization is 50%, it might prove a useful tool material.

The capability to use a.c. for useful E.C. machining is established, but whether or not there is more advantage than simply a saving in rectifier cost compared with d.c. use will only be determined by such factors as accuracy, repeatability, stability of operation and, perhaps, by the ability to machine materials which otherwise present difficulties.

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